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Acoustic emission monitoring of the bending under tension test

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Abstract

Preliminary investigations have shown that acoustic emission has promising aspects as an online monitoring technique for assessment of tribological conditions during metal forming as regards to determination of the onset of galling. In the present study the acoustic emission measuring technique has been applied for online monitoring of the frictional conditions experienced during Bending Under Tension (BUT) testing. The BUT test emulates the forming conditions experienced when drawing sheet material over a die curvature as in deep drawing processes. Monitoring of the developed acoustic emission in BUT testing has been found to describe the frictional conditions during forming well and to allow for accurate assessment of the limits of lubrication.

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Keywords: Acoustic emission monitoring; Tribology; Bending under tension testing;

Nomenclature

AE	Acoustic emission
BUT	Bending under tension
FFT	Fast Fourier transform
F_b	Back tension force
F_f	Drawing force
T	Torque

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1. Introduction

Galling is a wear phenomenon commonly encountered in various sheet metal forming processes, often occurring when working with tribologically difficult materials such as stainless steel, Al- or Ti-alloys. The galling mechanism is characterized as a localized macroscopic transfer of metallic material between contacting surfaces where surface damage progressively increases in severity. The occurrence of galling is a major concern in sheet stamping industry, since it leads to poor surface quality, production stops and tool deterioration. It is reported that galling wear accounts for up to 71% of the cost of die maintenance [1][2]. Online process monitoring of sheet metal forming operations is therefore of significant interest in order to actively minimize the occurring wear in production. Since the galling mechanism occurs in the contacting interface between the sheet metal and the forming die, the requirement for online process monitoring for sheet metal forming calls for an indirect measuring technique with sufficiently high sensitivity to detect any minute differences in the process. Conventional techniques, e.g. measurement of the forming force, have typically been found to have too limited sensitivity for assessment of the limits of lubrication [3]. Measurement of acoustic emission (AE) has, on the other hand, been successfully applied as an online monitoring technique for evaluation of different tribological characteristics in different metal forming operations [4]–[7]. Behrens *et al.* [8] have concluded that acquisition and analysis of AE signals allows for online assessment of production conditions and deviations in production processes. Skåre [9] similarly noted that energy analysis of the AE signals allows for an evaluation of the quality of lubrication and detection of process defects in sheet forming such as the stick-slip effect and cracking. Mostafavi and Pashmforoush [4] successfully applied the AE technique for detecting the onset of galling in a slider-on-sheet test, noting a direct relation between the wear mechanism and AE peak amplitudes.

Preliminary investigations by the present authors on detecting the onset of galling in strip reduction testing [11] have similarly shown a correlation between the development of the signal and the generated surface roughness, allowing for an assessment of the severity of the wear mechanism by comparing the developed AE signal with a reference threshold value. The strip reduction test is, however, a tribologically severe sheet forming test, which due to the large normal pressures, surface expansion and increase in temperature during testing results in severe galling in case of insufficient lubrication. For such cases the AE technique proves sound. In case of milder tribological tests e.g. strip drawing and bending under tension testing emulating deep drawing, where minor levels of galling may appear, investigations are required for characterization of the correlation between the frictional conditions and the generated AE signals. The aim of the present study is therefore to explore the possibility to apply the AE technique for tribological tests where mild galling occurs.

2. Experimental procedure

2.1 Bending under tension test

The BUT tests are conducted on a preexisting test setup, initially described by Andreasen *et al.* [10] shown in figure 1. The test replicates the tribological conditions experienced in the die curvature in a deep drawing process by drawing plane strip material over a die shoulder with superimposed back tension.

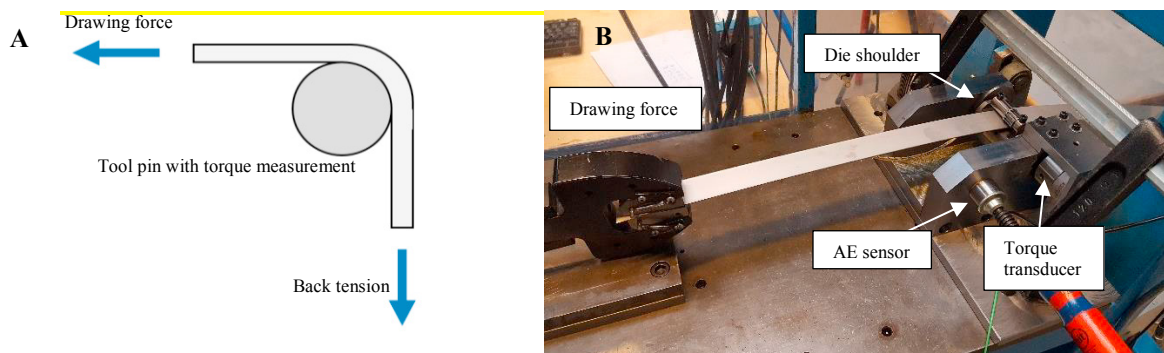


Fig. 1: Schematic illustration of the BUT test principles (A). Experimental BUT test setup (B).

The BUT test was conducted by drawing 800x30x1 mm strips of 304L stainless steel over a fixed Ø10mm tool of powder metallurgical high-speed steel DIN. W. No. 1.3344 PM, polished to a surface roughness $R_a = 0.1$. Constant back tension force $F_b = 6$ kN was applied with a drawing length of 150mm, while the drawing speed was approximately 300 mm/s. During the BUT test the horizontal drawing force, F_t and the torque on the tool pin was measured with piezoelectric transducers. Two separate test series were carried out for assessment of the accumulated wear occurring over time. They both included consecutively drawing of three steel strips on the same tool pin surface. The strips in the two test series were lubricated with two different, plain mineral oils, CR5 Houghton Plunger with a kinematic viscosity $\eta = 660$ cSt at 40°C and 50/50 wt.% CR5/Sun60, respectively. Sunoco Sun60 has a viscosity $\eta = 10$ cSt at 40°C. The mixture yields a viscosity of 60 cSt at 40°C. It was attempted to apply the same amount of lubricant on each strip. However this may be difficult to achieve in practice and is therefore a possible source of error.

Upon measurement of the drawing force and the torque during testing, the average friction stress and normal pressure in the tool/workpiece contact area can be determined.

$$\text{Friction stress: } \tau = \frac{2T}{\pi w R^2} \quad (1)$$

$$\text{Normal pressure: } p = \frac{F_f + F_b}{2wR} \quad (2)$$

2.2 Acoustic emission data acquisition

Data acquisition of the generated AE signals during BUT testing were made with a R15α piezoelectric sensor connected to a 2/4/6 analog preamplifier with a built-in bandpass filter of 10-900 kHz. The piezoelectric AE sensor was fixed to the pin tool holder with a clamping tool as close as possible to the tool pin. The contact area between sensor and tool holder was provided with grease paste as an acoustic couplant. The preamplifier was connected to a NI 9223 multipurpose data acquisition unit which was fixed to a NI 9146 4-slot expansion chassis. A sampling rate of 1 MHz with resolution of 16-bit was selected in order to suppress aliasing of the signal and any possible loss of signal amplitude.

3. Experimental results

3.1. Surface structure after BUT testing

The generated surface structure of the strips after BUT testing can be seen in figure 2. SEM images of the tested workpiece strips are shown in detail in figure 3. The legends A-D in figure 3 refers to the tests and strip locations shown in figure 2.

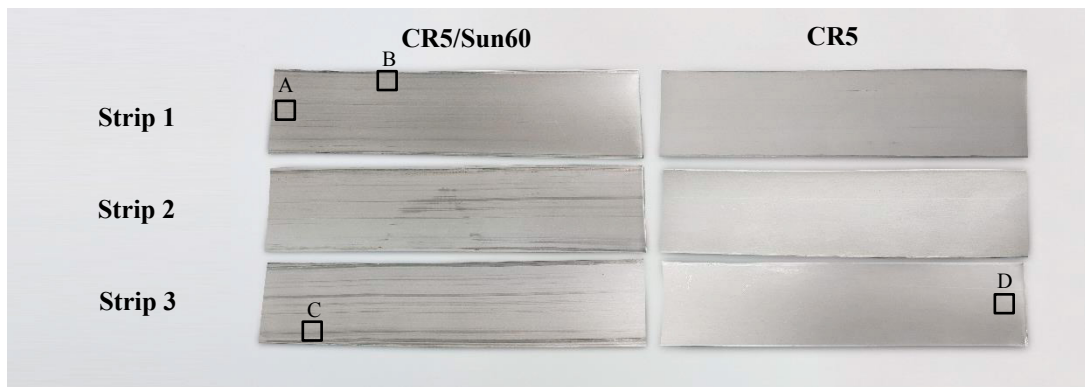


Fig. 2. Overview of the surface structure of the strips upon bending under tension testing with the CR5/Sun60 and CR5 lubricants.

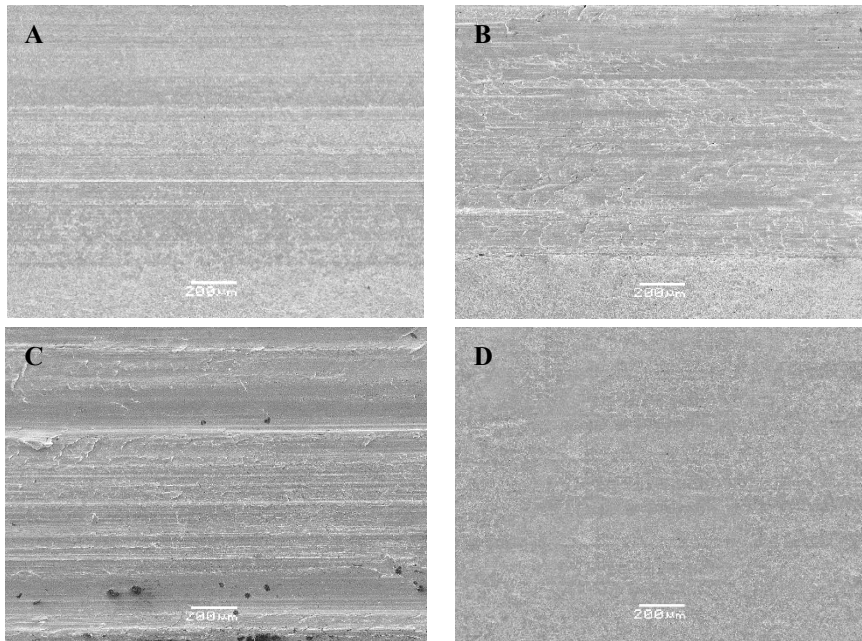


Fig. 3: SEM images of the surface structure upon BUT testing. (A) Minor levels of initial abrasive wear. (B) The onset of galling. (C) Galling with increased severity. (D) Completely smooth surface structure.

The SEM images in figures 3A, 3B and 3C illustrate the development of galling mechanism during BUT testing with the low viscous oil. Upon initial drawing of the strip with insufficient lubrication minor levels of scoring are observed as seen in figure 3A. At the onset of galling, local pickup on the tool has occurred leading to subsequent scoring of the strip surface upon further drawing, as seen in figure 3B. Upon further drawing of the strip material, the local pickup on the tool increases and the strip is scored more heavily as seen in figure 3C. Figure 3D represents an experiment with no galling obtained by running with the high viscous CR5 oil.

3.1 Drawing force and torque measurements

In figure 4 the developed drawing force and torque is shown as a function of the accumulated drawing lengths in the BUT test for the two lubricants. Minor fluctuations are noted in the force and torque measurements in the start and end of each dataset, due to start and stoppage of the drawing sequence [10].

Lubrication with CR5/Sun60 shows a gradual increase in the torque, which is due to the increased galling, since this phenomenon is directly related to the friction on the tool pin as shown in eq. 1. The measured drawing force is noted to have a significantly lower sensitivity towards changes in frictional conditions during the test than the torque. Previous BUT tests have [10] similarly found that the torque is more sensitive to changes in friction and enabling accurate assessment of lubricant film breakdown, while the measured drawing force generally has very low sensitivity for assessment of galling, when this is mild. The first strip within this test series is noted to have a stable development of the torque in the beginning, where only mild abrasive wear is observed on the strip surface. However at a drawing length of approximately 50mm a rampant development of the torque initiates. This point coincides with localized development of friction junctions in the surface structure, which indicates the initial stage of galling. At further drawing progressive scoring of the strip surfaces appears. The test series lubricated with the high viscosity CR5 lubricant is on the other hand found to have completely stable development of the drawing force and torque, with a significantly lower torque value. This corresponds to the smooth surface structure obtained in this test series with no sign of galling.

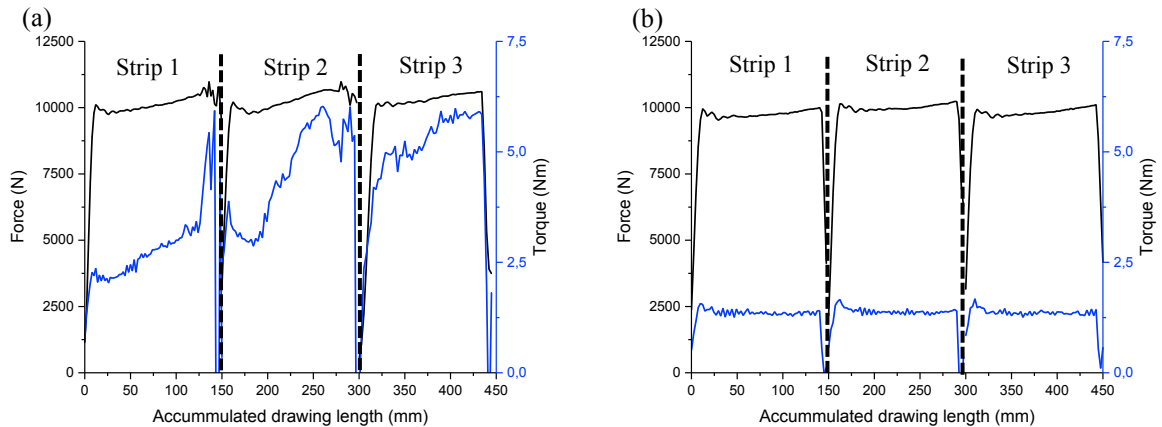


Fig. 4. Drawing force and torque experience during the BUT test lubricated with (a) CR5/Sun60, (b) CR5.

3.2 AE measurements

The instantaneous power of the acquired AE signal during the BUT test is displayed in figure 5. The red the AE signal which represents the test on CR5 lubricant, shows a very low and stable signal. This is due to the efficient lubrication and the resulting low frictional forces between workpiece and tool pin. The tested strip surface is smooth and no pick-up appears on the tool surface. The much stronger and fluctuating blue AE signal represents the test on CR5/Sun60 lubricant. The strong signal is due to thinning of the lubricant film, which causes increased friction and mild abrasive wear at first, followed by onset of galling at approximately 50 mm drawing length as noticed in the SEM images. Upon further drawing of the strip, the increased galling is reflected in the increased amplitude of the AE signal, which in general follows a similar trend as the measured torque. Comparison of the two test series with the two different lubricants thus indicates a very high signal to noise ratio. This allows for a simple way of detecting galling by acoustic emission using simple time domain parameters.

Regarding the blue AE signal in figure 5 for the strip lubricated with Cr5/Sun60, several local minima are observed for instance at 118, 200, 230 and 265mm drawing length with corresponding maxima in between, which are not all reflected in the torque signal. This is explained by the stick-slip occurring due to galling, which releases sudden signals, when local adhesion junctions between tool and workpiece are breaking. The torque measurement may not be able to capture these sudden fluctuations. The results, however, clearly indicate a strong correlation between galling and the transient stress waves acquired by the piezoelectric AE sensor. The limits of lubrication can thus be determined by evaluating the development of the acquired AE signal during testing. In order to implement the technique to manufacturing production proper choice of signal processing should be based upon the characteristics of the monitored process and the overall objective of monitoring. A few studies [4], [11] have however found that the galling wear occurring in metal forming production can be evaluated by assessment of simple AE parameters e.g. RMS and count-rate.

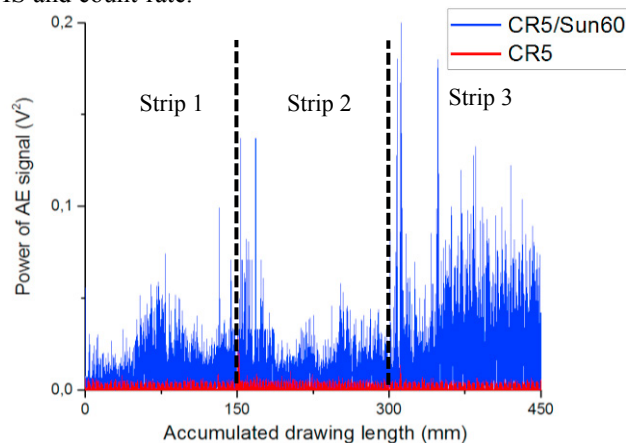


Fig. 5. Power of the generated AE signal throughout the BUT test.

A fast Fourier transform (FFT) showing the overall frequency components of the signals is displayed in figure. 6. From the frequency representation of the two signals, a major frequency component can be found when lubricating with CR5 at a frequency of 40 kHz. Several minor peaks can similarly be identified, however these are likely due to influencing noise factors, due to the low amplitudes. The frequency composition in the test setup lubricated with CR5 therefore characterises the naturally occurring frequencies with the specific test setup without the occurrence of galling. However, when galling occurs in the BUT test, a larger amplitude of the frequency spectra is noticed. This is seen as a significant amplitude increase in the measured frequencies in the range of 20-160 kHz. The change in the frequency spectrum can therefore be attributed to the occurrence of galling, since the spectrum increases progressively in amplitude as the wear mechanism develops.

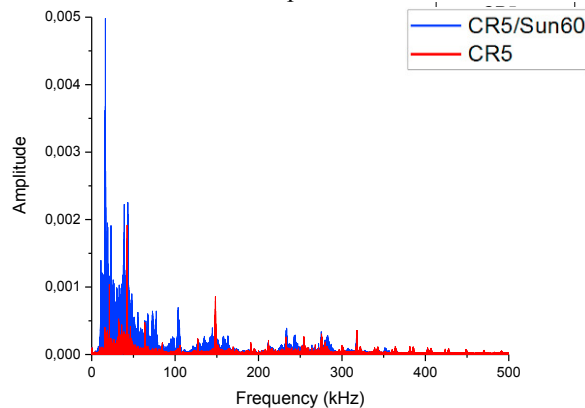


Figure 6. Frequency domain representation of the signal generated in with the two lubricants.

4. Conclusion

The AE measuring technique has been found to be a powerful tool for online monitoring of galling during BUT testing. By measuring the generated AE assessment of the limits of lubrication can be made and even very mild levels of wear can be detected. The generated AE was found to be correlated to the severity of galling. This was evaluated by visual inspection of the generated surface structure as well as by assessment of the friction stress experienced during testing. The generated AE signal caused by galling was furthermore found to occur especially in the low frequency range of 20-160 kHz. Assessment of the development of the captured AE signal therefore allows for an online evaluation of galling in sheet stamping production with relatively cheap and simple measuring equipment. This can prove valuable for process monitoring e.g. in complex forming dies where torque measurements cannot be applied.

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